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# Dynamics of localized solutions for reaction-diffusion systems on two dimensional domain - Spot dynamics on curved surface-

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## 1 Introduction

In nature, many kinds of spatial and/or temporal patterns are observed, some of them are simple and the others are complicated. To understand theoretically the dynamics of such patterns, many model equations have been proposed and analyzed. Among them, some sort of reaction-diffusion systems are one of the most familiar classes.

In this report, we consider general type of reaction-diffusion systems in  $\mathbf{R}^2$  which possess stable spot solutions. Spot patterns are one of the most typical and important patterns from the phenomenological point of view. In fact, spot patterns correspond to localized patterns of materials which are observed in many phenomena such as biology and chemistry. Also in mathematical models, many model equations with spot solutions have been proposed as in the Gierer-Meinhardt model, Gray-Scott model (e.g. [5], [4], [7], [8] ).

In this report, we assume the existence of a stable spot solution on  $\mathbf{R}^2$  and the dynamics of it on a curved surface in  $\mathbf{R}^3$ . A curved surface is imaged as a cell membrane and a spot solution is a localized structure with high density of materials on the surface. In fact, [1] reported the localization of the phosphatidylinositol lipids on the cell membrane of Dictyostelium cells. As the consequence, we show that the motion of spot solution along the surface is essentially described as the gradient flow of the Gaussian curvature.

## 2 Setting and results

In this section, we will give the several assumptions in the general framework.

Let us consider general type of reaction-diffusion systems written by

$$\mathbf{u}_t = D\Delta\mathbf{u} + F(\mathbf{u}), \quad t > 0, \quad \mathbf{x} \in \mathbf{R}^2, \quad \mathbf{u} \in \mathbf{R}^N, \quad (2.1)$$

where  $D$  is a diagonal matrix given by  $D := \text{diag}\{d_1, d_2, \dots, d_N\}$  with  $d_j > 0$  and  $F$  is a smooth map from  $\mathbf{R}^N$  to  $\mathbf{R}^N$ .

Let  $\mathcal{L}(\mathbf{u}) := D\Delta\mathbf{u} + F(\mathbf{u})$  and  $X := \{L^2(\mathbf{R}^2)\}^N$ . The assumptions are as follows:

- 1) There exist a radially symmetric stationary pulse solution  $S(r)$  of (2.1) such that  $\mathcal{L}(S(r)) \equiv 0$ , where  $r := |\mathbf{x}|$ .

Let  $L$  be the linearized operator  $\mathcal{L}'(S(r))$  of (2.1) with respect to  $S(r)$ , that is,  $L := D\Delta + {}^tF'(S(r))$ .

- 2) The spectral set of  $L$  consists of two sets  $\sigma_1 = \{0\}$  and  $\sigma_2 \subset \{\lambda \in \mathbf{C}; \text{Re}(\lambda) < -\gamma\}$  for a positive constant  $\gamma$ .

**Remark 2.1**  $0$  is necessarily a spectrum of  $L$  because (2.1) has a translation invariance and  $LS_{x_j} = 0$  ( $j = 1, 2$ ) hold, where  $\mathbf{x} = (x_1, x_2)$ .

Let  $Q$  and  $R$  be projections corresponding to the spectral sets  $\sigma_1$  and  $\sigma_2$ , respectively. That is,  $Q := \frac{1}{2\pi i} \int_C (\lambda - L)^{-1} d\lambda$  and  $R := Id - Q$ , where  $C$  is a circle around 0 inside  $\{\lambda \in \mathbf{C}; \text{Re}(\lambda) > -\gamma\}$  and  $Id$  denotes the identity. Define  $E := QX$ ,  $E^\perp := RX$ .

- 3)  $E = \text{span}\{S_{x_1}, S_{x_2}\}$  holds.

**Remark 2.2** The assumption 3) means the stability of  $S(x)$  except translation.

Let  $L^*$  be the adjoint operator of  $L$ . Then  $L^*$  also has eigenfunctions  $\phi_j^*(\mathbf{x})$  ( $j = 1, 2$ ) such that  $L^*\phi_j^* = 0$  and  $\langle S_{x_j}, \phi_j^* \rangle_X = \pi$ . Then we note that  $\phi_j^*$  is represented as  $\phi^* = \partial_{x_j} \Phi^*$  by a radially symmetric function  $\Phi^* = \Phi^*(r)$ .

Under these three assumptions, we consider the reaction-diffusion systems (2.1) on a smoothly curved surface  $\mathcal{M} \subset \mathbf{R}^3$ :

$$\mathbf{u}_t = \delta^2 \Delta_{\mathcal{M}} \mathbf{u} + F(\mathbf{u}), \quad t > 0, \quad \mathbf{x} \in \mathcal{M}, \quad (2.2)$$

where  $\delta > 0$  is a sufficiently small constant and  $\Delta_{\mathcal{M}}$  is the Laplace-Beltrami operator on  $\mathcal{M}$ .

For simplicity, we assume the surface  $\mathcal{M}$  is expressed by the isothermal coordinate as  $\mathcal{M} = \{\Gamma(u, v); (u, v) \in \mathbf{R}^2\}$  with  $ds^2 = E(u, v)(du^2 + dv^2)$ . Let  $K(u, v)$  be the Gaussian curvature of  $\mathcal{M}$  and  $T := \delta^2 t$ . Then we have:

**Theorem 2.1** *For  $\mathbf{H} \in \mathcal{M}$ , there exists a map  $\Psi = \Psi(\mathbf{w}; \mathbf{H}) \in \mathbf{R}^2$  defined for  $|\mathbf{w}| \ll 1$  such that  $\Psi(0; \mathbf{H}) = 0$  and the solution  $\mathbf{u}(t, \mathbf{x})$  of (2.2) is expressed as*

$$\mathbf{u}(t, \mathbf{x}) = S(|\Psi(\mathbf{x} - \mathbf{H}(T); \mathbf{H}(T))|/\delta) + O(\delta)$$

and  $\mathbf{H}(T)$  satisfies

$$\frac{d\mathbf{H}}{dT} = \frac{M_0}{E(\mathbf{h}(T))} \{K_u(\mathbf{h}(T))\Gamma_u(\mathbf{h}(T)) + K_v(\mathbf{h}(T))\Gamma_v(\mathbf{h}(T))\} + O(\delta), \quad (2.3)$$

where  $\mathbf{H} = \Gamma(\mathbf{h}) \in \mathcal{M}$ ,  $\mathbf{h} = (h_1, h_2) \in \mathbf{R}^2$ ,  $M_0 := \frac{3}{4} \int_0^\infty r^3 \langle DS_r, \Phi_r^* \rangle dr$ .

(2.3) implies that the spot solution moves toward points with maximal Gaussian curvature if  $M_0$  is positive and toward points with minimal Gaussian curvature if  $M_0$  is negative while the sign is depending on each model. The proofs will be basically given by similar manner to [2].

Finally, we give the explicit value of the constant  $M_0$  for the Gierer-Meinhardt model. We consider the following Gierer-Meinhardt model for sufficiently small  $\varepsilon > 0$ ,  $0 \leq \tau \ll 1$  and  $a > 0$ :

$$\begin{cases} u_t &= \varepsilon^2 \Delta u - u + \frac{u^{p_1}}{(v+a)^{p_2}}, \\ \tau v_t &= d \Delta v - v + \frac{u^{p_3}}{(v+a)^{p_4}}, \end{cases} \quad (2.4)$$

where  $p_j$  are the positive constants satisfying  $p_1 > 1$  and  $0 < \frac{p_1 - 1}{p_2} < \frac{p_3}{p_4 + 1}$ . (2.4) has a stable radially symmetric spiky solution in the form of  $S(r) = (U(r/\varepsilon), V(r))$  for  $r = |\mathbf{x}|$  and functions  $U(r)$ ,  $V(r)$  ([3], [5], [6]). In particular, when  $p_3 = 2$  and  $1 < p_1 < 3$  or  $p_3 = p_1 + 1$  and  $1 < p_1 < \infty$ ,  $\Phi^*(r)$  is given by  $\Phi^*(r) = c(U(r/\varepsilon), 0) + o(1)$  as  $\varepsilon \downarrow 0$  ([3]) for a constant  $c$ . Then we have the following theorem on the value of the constant  $M_0$ :

**Theorem 2.2** *If  $p_3 = 2$  and  $1 < p_1 < 3$  or  $p_3 = p_1 + 1$  and  $1 < p_1 < \infty$  are satisfied for (2.4), then the constant  $M_0$  is given by*

$$M_0 = \varepsilon^3 \frac{3 \int_0^\infty r^3 (U'(r))^2 dr}{4 \int_0^\infty r (U'(r))^2 dr} + o(\varepsilon^3) > 0.$$

The above theorem says that the spot solution moves toward points with maximal Gaussian curvature.

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